LS-12

K. Thompson/R. Lari
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# First Designs and Cost Estimates for the Storage Ring Dipoles and Quadrupoles


## Summary

The magnets described in this report are defined in reports LS-1 and LS-2. The required number considered here for each type of quadrupole resulted from the assumption that 16 insertion device straight sections were for undulators and 16 were for wigglers. A list of the major design criteria for the magnets is given and the results of the designs and the cost estimates obtained with the computer program MADEST are summarized. A total cost for the fabrication of these magnets is estimated to be $6578.5 K. Also included are descriptions of the magnetic field calculations for the dipole magnet that were done using the computer programs TRIM, PE2D, and POISSON. These produced data on the vertical field shape in the radial direction for a flat pole dipole. These results permitted the magnitudes of the harmonic components in the radial field distribution and the track of an electron through a dipole to be estimated.

Contents

Page

## MADEST CALCULATIONS

The dipole and quadrupole magnet designs for the storage ring have been designed with the computer program MADEST. The program was also used to calculate the costs of the resulting magnets. Since the costs of these magnets are a large part of the total cost of the entire complex, the costing methodology had to be checked.

These checks involved the design and cost estimating of the dipoles and some quadrupoles in other electron facilities, some of which have been built. The comparisons were done for the costs appearing in the corresponding proposals for PEP (Stanford, 1975), CESR (Cornell, 1975), CHEER (FNAL-Canada, 1980), and NCAM (Lawrence Berkeley, 1983).

Our cost calculations are presently based on data that has been developed through the GEM, Julich, and ASPUN projects in the last several years, and through many years of collective experience in the fabrication of many magnets for the ZGS, the IPNS RCS, and the FNAL electron cooling ring and of prototype sector magnets for GEM.

Using this data the costs for the PEP and CESR magnet were higher than those that were proposed in 1975. There was, however, agreement to within 10% for the later machines at NCAM and CHEER. We are, therefore, presently using our 1983 data for the SLS magnets which can be easily adjusted for inflation.

From here the designs for the storage ring magnets for the 6 GeV Synchrotron Light Source (SLS) were developed based on parameters specified in reports LS-1 and LS-2. We also tried to include in these designs many of the same criteria used for the magnet designs in the electron facilities covered in the proposals listed above and the European Synchrotron Light Source (ESRP). The gap parameters as specified in LS-1 and LS-2 are summarized below:

Storage Ring Magnets
Original Gap Parameters

| Magnet Type | Quantity | L (m) | B or B' (T) or (T/m) | Aperture (cm) |
|---|---|---|---|---|
| M | 64 | 2.95 | 0.6661 | 6.5H x 14W |
| QD1 | 32 | 0.7 | -4.292 | 6.5 dia |
| QF2 | 32 | 1.0 | 18.385 | 6.5 dia |
| QD3 | 32 | 0.7 | -17.649 | 6.5 dia |
| QD4 | 64 | 0.7 | -7.499 | 6.5 dia |
| QF5 | 64 | 0.7 | 10.863 | 6.5 dia |
| QD6 | 32 | 0.7 | -11.900 | 6.5 dia |
| QF7 | 32 | 1.0 | 8.880 | 6.5 dia |

The quadrupole magnets form four groups, each covering a different strength range and, therefore, requiring different coils. The parameters for these combined cross-section designs are listed below:

Storage Ring Magnets
Combined Gap Parameters

| Magnet Type | B' (T/m) | Aperture (cm) |
|---|---|---|
| QF2/QD3 | 19.0 | 6.5 dia |
| QF5/QD6 | 12.0 | 6.5 dia |
| QD4/QF7 | 9.0 | 6.5 dia |
| QD1 | 5.0 | 6.5 dia |

Some of the other primary magnet characteristics are summarized below:

1. All magnets shall be compatible with the double-chamber design of the vacuum chamber as described in notes from the Vacuum Task Group since November 1-- major dimensions were defined about mid-November.
2. Magnet cores to be made from laminated steel 1.5mm thick. This will allow the cores to be magnetically matched by shuffling the laminations. Also it allows total freedom to specify the pole tip shapes including edge shims.
3. The back and top yoke thicknesses of the dipole C-core shall be thick enough to keep the gap height deflections at 6 GeV to less than about 0.025 mm - this was the PEP criteria and corresponds to a 0.04% change in gap height.

4. The magnets shall be parallel stacked with magnet steel end plates made from magnet steel and welded tie bars. The dipoles will be curved by pressing laminations against a curved bar at the appropriate radius before welding.

5. The quadrupole cores shall have only top and bottom yokes. This not only keeps the midplane clear for the vacuum chamber but also maintains the magnet symmetry. A C-core disrupts right-left symmetry and would greatly complicate the shim design. The upper and lower magnet halves can be supported by a stainless steel strong-back bolted to the inside radius faces.

6. The dipole supply currents shall be less than 1000A and the quadrupole currents respectively shall be less than 500A. This would require two and one, respectively, 535MCM cables for each interconnection run.

7. All coils shall have only one potted assembly per pole. The dipole coils must fit through the gap.

8. The dipole coils shall have current densities in the copper conductor of around 2.5A/mm$^2$. Values like this are often quoted as being "optimum." The coils shall have a W/H ratio of around 2, and the vertical distance between the two coils shall be large enough to clear the vacuum chamber, anti-chamber. They shall also have at least two layers of conductor on each pole to prevent having electrical and cooling connections next to the core. Therefore, there will be only one water circuit per pole. This could allow us to have only three water hoses per magnet or maybe even one.

9. The quadrupole coils shall also have current densities in the copper conductors of around 2.5A/mm$^2$. The coils shall be shaped to keep the area around the midplane clear for the vacuum chamber. The same conductor shall be used in all quadrupoles and the coolant hole shall be around 0.5 times the outside width to assure that the conductor can be made. There shall be no more than four cooling circuits per magnet keeping the number of hoses to a minimum.

10. The coolant water system shall be capable of supplying a 100 psi pressure gradient across each magnet and a supply temperature of no larger than 38° C. These are typical values for the IPNS RCS accelerator. The temperature gradient across each magnet shall be less than about 17° F.

The dipole gap deflections were estimated by R. Wehrle for a case with a 21 cm wide pole and a 21 cm wide yoke. He found the deflections are less than .025 mm and were consistent with those he found using the same methodology for the PEP dipole. We, therefore, have generalized by keeping the yoke equal to the 14 cm pole width in the latest design.

The preliminary design for the dipole is summarized in Table I and the cost data is shown in Table II and a summary of the dipole costs is presented in Table III. A sketch of the dipole and vacuum chamber is shown in Figure 1.

A number of coils were designed for the QF5/QD6 quadrupole and it was noted that power losses could vary from about 4kW to less than 1kW per magnet depending on how many conductors were placed in the coil on each pole. It was decided that the coil should be made from only one, series connected conductor with enough copper to keep the power losses to about 2kW per magnet. This is a fairly low value and allows each quad to be cooled with only one circuit. This could possibly eliminate the water hoses on the quads making very durable magnets.

The design for the QF5/QD6 quad is summarized in the parameter list in Table IV. This is a representative example of the quad cases. The cost data for the quadrupoles is shown in Table V an example of the quadrupole cost tables is shown in Table VI for the QF5/QD6 magnet. A sketch of the cross section of the QF5/QD6 quad and the vacuum chamber is shown in Figure 2. A summary of some of the design results and the costs for the eight magnets for the storage ring is given in Table VII.

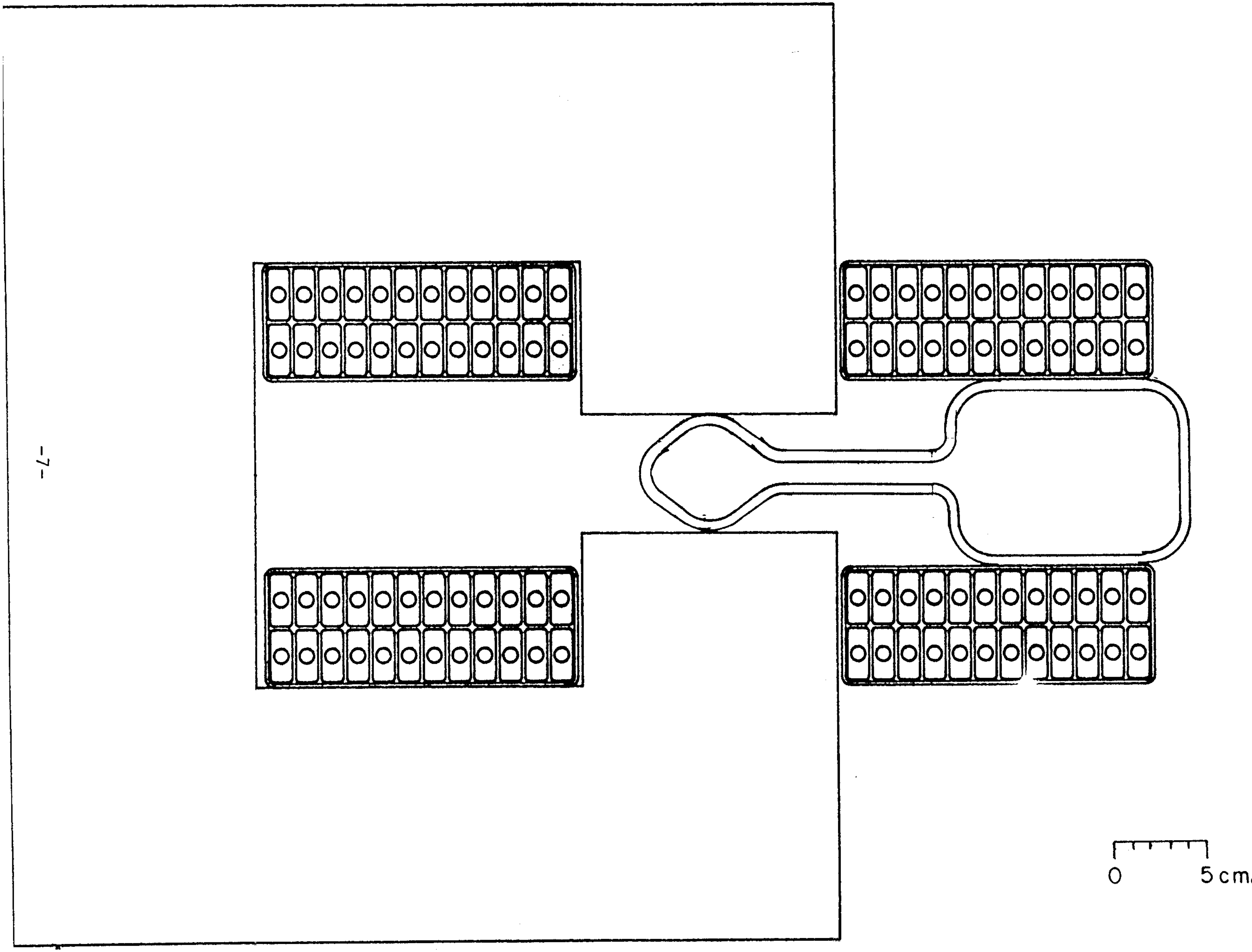



Figure 1 - Storage Ring Dipole and Vacuum Chamber

TABLE I

Storage Ring Dipole Design

| | | |
|---|---|---|
| DESIGN PARAMETERS of MAGNET SYSTEM: | | |
| Number of magnets | = | 64 |
| Type of magnet | = | Dipole HF |
| Type of excitation | = | Simple AC |
| Repetition frequency | (Hz)= | 0 |
| Dipole field strength | (G)= | 6661 |
| DESIGN and OPERATING PARAMETERS of a SINGLE MAGNET: | | |
| *Vacuum chamber* | | |
| Chamber type | = | None |
| *Gap* | | |
| Gap axis shape | = | Curved |
| Effective length of field along gap axis | (cm)= | 295 |
| Total width of pole | (cm)= | 14 |
| Total gap height | (cm)= | 6.5 |
| *Core* | | |
| Distance from-Field edge to-Core end | (cm)= | 3.25 |
| -Pole side | (cm)= | 3.25 |
| -Coil to-Pole face | (cm)= | 1.85 |
| -Pole side | (cm)= | .25 |
| -Top yoke | (cm)= | 0 |
| -Side yoke | (cm)= | .5 |
| -Endplate end | (cm)= | .5 |
| Maximum average field density inside yoke | (G)= | 9753 |
| Ratio of side yoke thicknesses(L/R) | = | 0 |
| Overall core-Height | (cm)= | 51.2 |
| -Width | (cm)= | 45.95 |
| -Length | (cm)= | 288.4 |
| Total mass of magnetic core | (kg)= | 4148 |
| Lamination thickness | (cm)= | .15 |
| Lamination stacking method | = | Parallel |
| Radius of curvature of gap axis | (cm)= | 3000 |
| End plate thickness | (cm)= | 2.54 |
| End plate material | = | Magnet st. |
| *Coil* | | |
| Conductor material | = | Copper |
| Conductor-Height | (cm)= | 2.85 |
| -Width | (cm)= | 1.2 |
| -Hole diameter | (cm)= | .8 |
| -Corner radius | (cm)= | .2 |
| Number of coolant holes | = | 1 |
| Conductor min. bend radius(inside edge)-Width | (cm)= | 5 |
| Insulation-Tape-Thickness-Turn | (cm)= | .05 |
| -Ground | (cm)= | .1 |
| -Width-Turn | (cm)= | 2.5 |
| -Ground | (cm)= | 2.5 |
| Insulation total thickness-Turn | (cm)= | .1 |
| -Ground | (cm)= | .2 |
| Average turn length | (cm)= | 654 |
| Hydraulic bend factor | = | 1.1 |
| Magnetic efficiency | (%)= | 90.6 |
| Ampere-turns per pole | (Amperes)= | 19012 |

TABLE I
(Continued)

| | | |
|---|---|---|
| Coil configuration definition | = | Manual |
| Number of layers of conductors per pole | = | 2 |
| Number of conductors per layer per pole | = | 12 |
| Effective number of turns per magnet | = | 48 |
| Number of turns per cooling circuit | = | 24 |
| Number parallel connected conductors per magnet | = | 1 |
| Coil-Height | (cm)= | 6.5 |
| -Width | (cm)= | 17.2 |
| *Electrical* | | |
| Stored energy | (J)= | 6940 |
| Total inductance | (mH)= | 22.1 |
| Total coil resistance | (mOhms)= | 20.84 |
| Supply current | (Amperes)= | 792 |
| Voltage across magnet | (Volts)= | 16.5 |
| Overall magnet-Height | (cm)= | 51.2 |
| -Width | (cm)= | 45.95 |
| -Length | (cm)= | 323.8 |
| Min. length from gap center to magnet edge-Vert. | (cm)= | 25.6 |
| -Horiz. | (cm)= | 24.95 |
| Total mass of an assembled magnet | (kg)= | 5044 |

OPERATING PARAMETERS of the MAGNET SYSTEM:

| | | |
|---|---|---|
| *Cooling circuit* | | |
| Coolant supply temperature | (C)= | 38 |
| Coolant temperature gradient | (C)= | 19.49 |
| Pressure gradient | (psi)= | 100 |
| Coolant flow | (gpm)= | 164.4 |
| *Power losses* | | |
| Electrical losses in magnets | (W)= | 837063 |
| Electrical power to operate coolant pumps | (W)= | 10217 |

TABLE II

Unit Cost and Effort for the Storage Ring Dipole

MISCELLANEOUS ASSUMPTIONS AND FABRICATION PARAMETERS:

| | | |
|---|---|---|
| Number of lamination parts | = | 1 |
| Number of stamping operations per lamination part | = | 1 |
| Number of core edges to machine | = | 2 |
| Number of coil pottings per pole | = | 1 |
| Core is potted | = | No |
| Mass of miscellaneous components | (kg)= | 45.45 |
| Average shipping distance | (km)= | 1448 |
| Shipping costs | ($/kg)= | 0 |
| Effort efficiency for work calculated in mhrs | (%)= | 80 |
| Operating life | (yr)= | 10 |
| Duty factor during operation | (%)= | 50 |
| Contingency | (%)= | 0 |

RAW MATERIAL COSTS:

| | | |
|---|---|---|
| Magnetic steel sheet | ($/kg)= | 1.76 |
| Low carbon steel | ($/kg)= | 1.1 |
| Copper conductor | ($/kg)= | 4.4 |
| Insulation tape-Turn | ($/cm)= | .001969 |
| -Ground | ($/cm)= | .001969 |
| Coil potting epoxy | ($/kg)= | 3.52 |
| Electric power | ($/kW-hr)= | .06 |

FABRICATED PARTS COSTS:

| | | |
|---|---|---|
| Laminations | ($/unit)= | .8 |
| Low-carbon steel end plates | ($/unit)= | 500 |
| Miscellaneous coil fittings | ($)= | 200 |
| Miscellaneous assembly fittings | ($)= | 400 |

TOOLING FABRICATION COSTS:

| | | |
|---|---|---|
| Lamination die | ($)= | 30000 |
| Core stacking fixture | ($)= | 12000 |
| Lamination edge machining fixture | ($)= | 4000 |
| Vapor degreaser for laminations | ($)= | 6000 |
| Coil-Winding fixture | ($)= | 6000 |
| -Potting fixture | ($)= | 8000 |
| Vacuum impregnation consumable hardware | ($)= | 100 |
| Alignment fixtures | ($)= | 0 |

EXCESSES INCLUDED:

| | | |
|---|---|---|
| Minimum number of spare magnets | (%)= | 0 |
| Low carbon steel | (%)= | 0 |
| Magnetic steel sheet | (%)= | 1 |
| Outter surface trim per machined side | (cm)= | 1 |
| Laminations | (%)= | .5 |
| Coil end lengths | (cm)= | 61 |
| Copper conductor | (%)= | 10 |

MISCELLANEOUS MATERIALS USAGE:

TABLE II
(Continued)

| | | | |
|---|---|---|---|
| 56 | Coil potting epoxy per insulation volume | (%)= | 75 |
| 57 | | | |
| 58 | LABOR COSTS: | | |
| 59 | | | |
| 60 | Technical staff(TS) | ($/mmo)= | 0 |
| 61 | Drafting(DR) | ($/mmo)= | 0 |
| 62 | Machinists(MA) | ($/mhr)= | 35 |
| 63 | Technician(TE) | ($/mhr)= | 35 |
| 64 | Riggers(RG) | ($/mhr)= | 35 |
| 65 | | | |
| 66 | FABRICATION EFFORT PER PROJECT: | | |
| 67 | | | |
| 68 | Magnet design-TS | (mmo)= | 1 |
| 69 | -DR | (mmo)= | 1.5 |
| 70 | Procurement & QC-TS | (mmo)= | 0 |
| 71 | Core stacking fixture-Design-TS | (mmo)= | .2 |
| 72 | -DR | (mmo)= | .5 |
| 73 | -Assem. & align.-TS | (mmo)= | .2 |
| 74 | -TE | (mhr)= | .5 |
| 75 | Coil tooling design-TS | (mmo)= | .2 |
| 76 | -DR | (mmo)= | .5 |
| 77 | Core tooling design-TS | (mmo)= | .3 |
| 78 | -DR | (mmo)= | .6 |
| 79 | Project administration-TS | (%)= | 0 |
| 80 | | | |
| 81 | FABRICATION EFFORT PER MAGNET: | | |
| 82 | | | |
| 83 | Core-Stacking-TE | (mhr/unit)= | .016 |
| 84 | -Edge machining-MA | (mhr)= | 12 |
| 85 | -Welding-MA | (mhr)= | 4 |
| 86 | -Assembly-TE | (mhr)= | 4 |
| 87 | -Moving-RG | (mhr)= | 2 |
| 88 | -Supervision-TS | (mmo)= | .05 |
| 89 | Coil-Application of turn insulation-TE | (mhr/wrap)= | .003 |
| 90 | -Winding-TE | (mhr/bend)= | .25 |
| 91 | -Brazing of cooling & elec. joints-TE | (mhr/joint)= | 4 |
| 92 | -Application of ground insulation-TE | (mhr/unit)= | 1 |
| 93 | -Potting-TE | (mhr/unit)= | 16 |
| 94 | -Tests-TE | (mhr/unit)= | 2 |
| 95 | -Supervision-TS | (mmo)= | .05 |
| 96 | Magnet assembly-Coil installation-TE | (mhr)= | 2 |
| 97 | -Cooling & elec. connections-TE | (mhr)= | 4 |
| 98 | -Tests-TE | (mhr)= | 8 |
| 99 | -Moving-RG | (mhr)= | 2 |
| 100 | -Supervision-TS | (mmo)= | .05 |

TABLE III
Major Costs for Fabricating Storage Ring Dipoles

Cost estimates for 64 magnets.

COSTS FOR FABRICATING THE MAGNETS:

| Purchased Materials and Parts | Quantity | | Cost (K$) |
|---|---|---|---|
| Magnetic steel | 372448 kg | | 651.3 |
| Laminations | 121480 | | 97.2 |
| End plate fabrication | 128 | | 64.0 |
| Copper conductor | 57162 kg | | 251.5 |
| Tape insulation | 17922570 cm | | 35.3 |
| Epoxy | 2056 kg | | 7.2 |
| Misc hardware | 2909 kg | | 44.8 |
| Shipping | 434575 kg | | 0.0 |
| | | Subtotal | 1151.3 |

| Effort | TS | DR | MA | TE | RG | | Cost (K$) |
|---|---|---|---|---|---|---|---|
| | | (man-months) | | | | | |
| Core-Machining | | | 5.5 | | | | 33.6 |
| -Assembly | | | 1.8 | 15.7 | .9 | | 112.0 |
| Coil-Winding | | | | 22.6 | | | 137.2 |
| -Insulating | | | | .9 | | | 5.6 |
| -Assembly | | | | 29.5 | | | 179.2 |
| -Potting | | | | 14.7 | | | 89.6 |
| -Testing | | | | 1.8 | | | 11.2 |
| Magnet-Assembly | | | 1.8 | 2.8 | | | 28.0 |
| -Testing | | | | 3.7 | | | 22.4 |
| Moving | | | | | .9 | | 5.6 |
| | | | 9.1 | 91.7 | 1.8 | Subtotal | 624.4 |

COSTS DISTRIBUTED OVER ENTIRE PROJECT:

| | TS | DR | MA | TE | RG | | Cost (K$) |
|---|---|---|---|---|---|---|---|
| Design-Tooling | .7 | 1.6 | | | | | |
| -Magnet | 1.0 | 1.5 | | | | | |
| Tooling-Fabrication | | | | | | | 66.0 |
| -Assembly | .2 | | | .2 | | | 1.4 |
| Supervision | 9.6 | | | | | | |
| | 11.5 | 3.1 | | .2 | | Subtotal | 67.4 |

Administration
Contingency

Grand Total 1843.1 x 1.1 = 2027.5 (1985$K)

| | TS | DR | MA | TE | RG |
|---|---|---|---|---|---|
| Effort totals | 11.5 | 3.1 | 9.1 | 91.9 | 1.8 |

To build and operate for 10 years at 4380 hours each is $4070 K.

Costs to Engineer-Design-Inspect-Administrate are 0% of the costs to build.

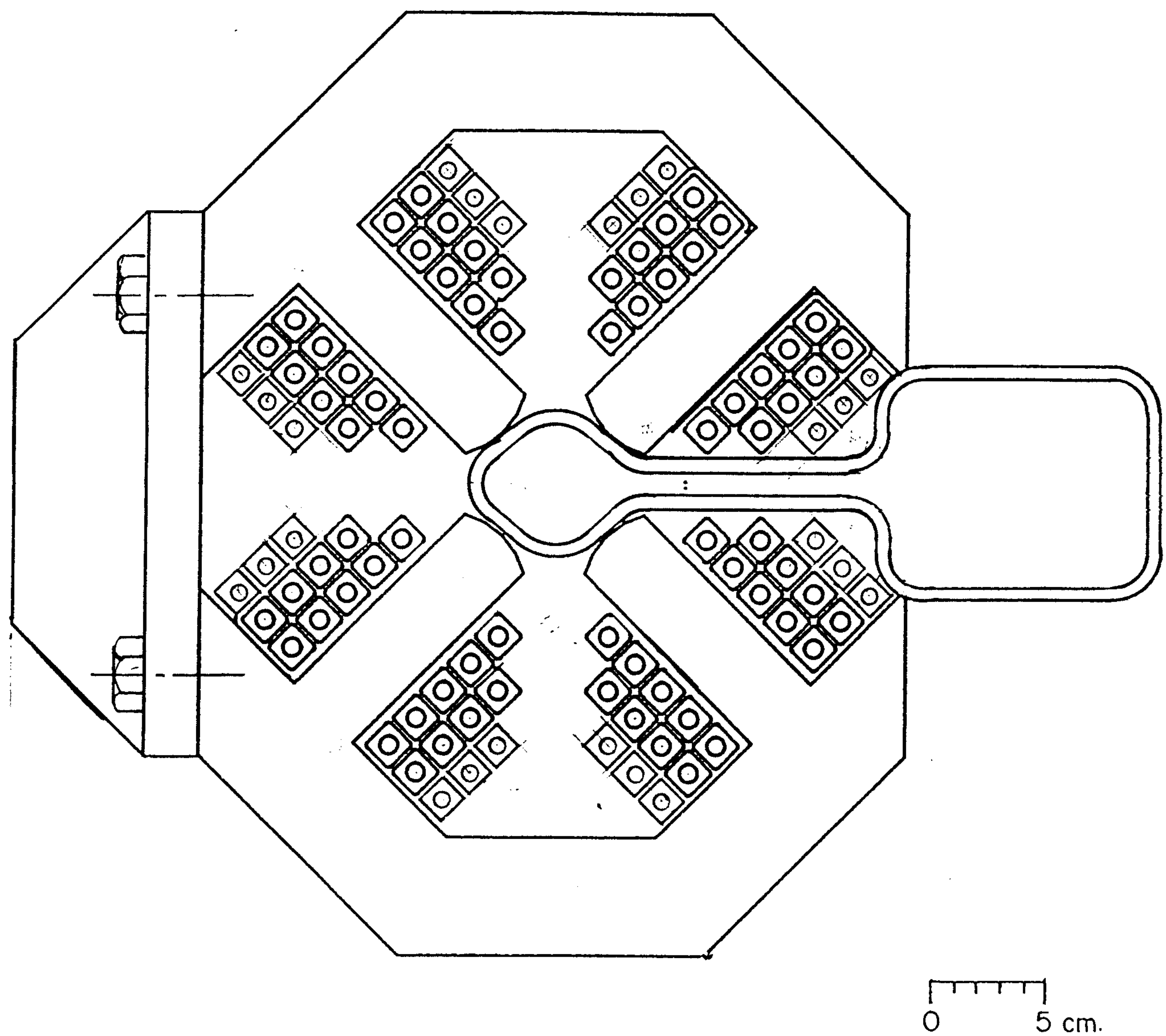



Figure 2 - Storage Ring QF5/QD6 Quad and Vacuum Chamber

TABLE IV

Storage Ring QF5/QD6 Quad Design

| | | |
|---|---|---|
| **DESIGN PARAMETERS of MAGNET SYSTEM:** | | |
| Number of magnets | = | 96 |
| Type of magnet | = | Quadrupole |
| Type of excitation | = | Simple AC |
| Repetition frequency | (Hz)= | 0 |
| Maximum multipole field gradient | (G/cm)= | 1200 |
| **DESIGN and OPERATING PARAMETERS of a SINGLE MAGNET:** | | |
| *Vacuum chamber* | | |
| Chamber type | = | None |
| *Gap* | | |
| Effective length of field along gap axis | (cm)= | 70 |
| Total width of pole | (cm)= | 3.705 |
| Total bore radius | (cm)= | 3.25 |
| *Core* | | |
| Distance from-Field edge to-Core end | (cm)= | 1.414 |
| -Coil to-Pole face | (cm)= | 0 |
| -Pole side | (cm)= | .15 |
| -Top yoke | (cm)= | 0 |
| -Side yoke | (cm)= | 2 |
| -Endplate end | (cm)= | 2 |
| Pole radius | (cm)= | 3.705 |
| Angle of pole | (deg)= | 60 |
| Angle between pole axis and pole side | (deg)= | 0 |
| Maximum field density at pole edge | (G)= | 5015 |
| Maximum average field density inside yoke | (G)= | 15000 |
| Ratio of side to top yoke thicknesses(S/T) | = | 0 |
| Overall core-Height | (cm)= | 41.77 |
| -Width | (cm)= | 31.3 |
| -Length | (cm)= | 67.2 |
| Total mass of magnetic core | (kg)= | 383 |
| Lamination thickness | (cm)= | .15 |
| Lamination stacking method | = | Parallel |
| End plate thickness | (cm)= | 1.5 |
| End plate material | = | Magnet st. |
| *Coil* | | |
| Conductor material | = | Copper |
| Conductor-Height | (cm)= | 1.5 |
| -Width | (cm)= | 1.5 |
| -Hole diameter | (cm)= | .8 |
| -Corner radius | (cm)= | .15 |
| Conductor min. bend radius(inside edge)-Width | (cm)= | 5 |
| Insulation-Tape-Thickness-Turn | (cm)= | .05 |
| -Ground | (cm)= | .1 |
| -Width-Turn | (cm)= | 2.5 |
| -Ground | (cm)= | 2.5 |
| Insulation total thickness-Turn | (cm)= | .1 |
| -Ground | (cm)= | .2 |
| Average turn length | (cm)= | 154.2 |
| Hydraulic bend factor | = | 1.1 |
| Magnetic efficiency | (%)= | 90 |
| Ampere-turns per pole | (Amperes)= | 5603 |

TABLE IV
(Continued)

| | | |
|---|---|---|
| Coil configuration definition | = | Manual |
| Number of layers of conductors per pole | = | 6 |
| Number of conductors per layer per pole | = | 2 |
| Effective number of turns per magnet | = | 48 |
| Number of turns per cooling circuit | = | 48 |
| Number parallel connected conductors per magnet | = | 1 |
| Coil-Height | (cm)= | 10.6 |
| -Width | (cm)= | 3.8 |
| *Electrical* | | |
| Stored energy | (J)= | 997 |
| Total inductance | (mH)= | 9.15 |
| Total coil resistance | (mOhms)= | 7.96 |
| Supply current | (Amperes)= | 466.9 |
| Voltage across magnet | (Volts)= | 3.718 |
| Overall magnet-Height | (cm)= | 41.77 |
| -Width | (cm)= | 31.3 |
| -Length | (cm)= | 78.8 |
| Min. length from gap center to magnet edge-Vert. | (cm)= | 20.88 |
| -Horiz. | (cm)= | 15.66 |
| Total mass of an assembled magnet | (kg)= | 547 |

<u>OPERATING PARAMETERS of the MAGNET SYSTEM:</u>

| | | |
|---|---|---|
| *Cooling circuit* | | |
| Coolant supply temperature | (C)= | 38 |
| Coolant temperature gradient | (C)= | 3.458 |
| Pressure gradient | (psi)= | 100 |
| Coolant flow | (gpm)= | 184 |
| *Power losses* | | |
| Electrical losses in magnets | (W)= | 166674 |
| Electrical power to operate coolant pumps | (W)= | 11433 |

TABLE V

Unit Cost and Effort for the Storage Ring Quads

**MISCELLANEOUS ASSUMPTIONS AND FABRICATION PARAMETERS:**

| | | |
|---|---|---|
| Number of lamination parts | = | 2 |
| Number of stamping operations per lamination part | = | 1 |
| Number of core edges to machine | = | 2 |
| Number of coil pottings per pole | = | 1 |
| Core is potted | = | No |
| Mass of miscellaneous components | (kg)= | 10 |
| Average shipping distance | (km)= | 1448 |
| Shipping costs | ($/kg)= | 0 |
| Effort efficiency for work calculated in mhrs | (%)= | 80 |
| Operating life | (yr)= | 10 |
| Duty factor during operation | (%)= | 50 |
| Contingency | (%)= | 0 |

**RAW MATERIAL COSTS:**

| | | |
|---|---|---|
| Magnetic steel sheet | ($/kg)= | 1.76 |
| Low carbon steel | ($/kg)= | 1.1 |
| Copper conductor | ($/kg)= | 4.4 |
| Insulation tape-Turn | ($/cm)= | .001969 |
| -Ground | ($/cm)= | .001969 |
| Coil potting epoxy | ($/kg)= | 3.52 |
| Electric power | ($/kW-hr)= | .06 |

**FABRICATED PARTS COSTS:**

| | | |
|---|---|---|
| Lamination parts | ($/unit)= | .8 |
| Low-carbon steel end plates | ($/unit)= | 500 |
| Miscellaneous coil fittings | ($)= | 200 |
| Miscellaneous assembly fittings | ($)= | 1.4 |

**TOOLING FABRICATION COSTS:**

| | | |
|---|---|---|
| Lamination die | ($)= | 20000 |
| Core stacking fixture | ($)= | 8000 |
| Lamination edge machining fixture | ($)= | 2500 |
| Vapor degreaser for laminations | ($)= | 6000 |
| Coil-Winding fixture | ($)= | 6000 |
| -Potting fixture | ($)= | 8000 |
| Vacuum impregnation consumable hardware | ($)= | 100 |
| Alignment fixtures | ($)= | 0 |

**EXCESSES INCLUDED:**

| | | |
|---|---|---|
| Minimum number of spare magnets | (%)= | 0 |
| Low carbon steel | (%)= | 0 |
| Magnetic steel sheet | (%)= | 1 |
| Outter surface trim per machined side | (cm)= | 1 |
| Laminations | (%)= | .5 |
| Coil end lengths | (cm)= | 61 |
| Copper conductor | (%)= | 10 |

**MISCELLANEOUS MATERIALS USAGE:**

TABLE V
(Continued)

| | | |
|---|---|---|
| Coil potting epoxy per insulation volume | (%)= | 75 |

LABOR COSTS:

| | | |
|---|---|---|
| Technical staff(TS) | ($/mmo)= | 0 |
| Drafting(DR) | ($/mmo)= | 0 |
| Machinists(MA) | ($/mhr)= | 35 |
| Technician(TE) | ($/mhr)= | 35 |
| Riggers(RG) | ($/mhr)= | 35 |

FABRICATION EFFORT PER PROJECT:

| | | |
|---|---|---|
| Magnet design-TS | (mmo)= | 1 |
| -DR | (mmo)= | 1.5 |
| Procurement & QC-TS | (mmo)= | 0 |
| Core stacking fixture-Design-TS | (mmo)= | .2 |
| -DR | (mmo)= | .5 |
| -Assem. & align.-TS | (mmo)= | .2 |
| -TE | (mhr)= | .5 |
| Coil tooling design-TS | (mmo)= | .2 |
| -DR | (mmo)= | .5 |
| Core tooling design-TS | (mmo)= | .3 |
| -DR | (mmo)= | .6 |
| Project administration-TS | (%)= | 0 |

FABRICATION EFFORT PER MAGNET:

| | | |
|---|---|---|
| Core-Stacking-TE | (mhr/unit)= | .012 |
| -Edge machining-MA | (mhr)= | 8 |
| -Welding-MA | (mhr)= | 8 |
| -Assembly-TE | (mhr)= | 16 |
| -Moving-RG | (mhr)= | 4 |
| -Supervision-TS | (mmo)= | .05 |
| Coil-Application of turn insulation-TE | (mhr/wrap)= | .003 |
| -Winding-TE | (mhr/bend)= | .25 |
| -Brazing of cooling & elec. joints-TE | (mhr/joint)= | 4 |
| -Application of ground insulation-TE | (mhr/unit)= | 1 |
| -Potting-TE | (mhr/unit)= | 16 |
| -Tests-TE | (mhr/unit)= | 2 |
| -Supervision-TS | (mmo)= | .05 |
| Magnet assembly-Coil installation-TE | (mhr)= | 2 |
| -Cooling & elec. connections-TE | (mhr)= | 8 |
| -Tests-TE | (mhr)= | 8 |
| -Moving-RG | (mhr)= | 2 |
| -Supervision-TS | (mmo)= | .05 |

TABLE VI

Major Costs for Fabricating Storage Ring QF5/QD6 Quad

Cost estimates for 96 magnets.

COSTS FOR FABRICATING THE MAGNETS:

| Purchased Materials and Parts | Quantity | Cost (K$) |
|---|---|---|
| Magnetic steel | 77622 kg | 134.4 |
| Laminations | 82539 | 66.0 |
| End plate fabrication | 192 | 96.0 |
| Copper conductor | 12225 kg | 53.8 |
| Tape insulation | 5314965 cm | 10.5 |
| Epoxy | 650 kg | 2.3 |
| Misc hardware | 960 kg | 28.9 |
| Shipping | 91457 kg | 0.0 |
| | Subtotal | 391.9 |

| Effort | TS | DR | MA | TE | RG | | Cost (K$) |
|---|---|---|---|---|---|---|---|
| | | (man-months) | | | | | |
| Core-Machining | | | 5.5 | | | | 33.6 |
| -Assembly | | | 5.5 | 14.5 | 2.8 | | 138.9 |
| Coil-Winding | | | | 33.5 | | | 203.7 |
| -Insulating | | | | 2.8 | | | 16.8 |
| -Assembly | | | | 8.3 | | | 50.4 |
| -Potting | | | | 44.2 | | | 268.8 |
| -Testing | | | | 5.5 | | | 33.6 |
| Magnet-Assembly | | | 5.5 | 6.9 | | | 75.6 |
| -Testing | | | | 5.5 | | | 33.6 |
| Moving | | | | | 1.4 | | 8.4 |
| | | | 16.5 | 121.2 | 4.2 | Subtotal | 863.4 |

COSTS DISTRIBUTED OVER ENTIRE PROJECT:

| | TS | DR | MA | TE | RG | | Cost (K$) |
|---|---|---|---|---|---|---|---|
| Design-Tooling | .7 | 1.6 | | | | | |
| -Magnet | 1.0 | 1.5 | | | | | |
| Tooling-Fabrication | | | | | | | 50.5 |
| -Assembly | .2 | | | .3 | | | 2.1 |
| Supervision | 14.4 | | | | | | |
| | 16.3 | 3.1 | | .3 | | Subtotal | 52.6 |

Administration
Contingency

Grand Total 1307.9x 1.1 = 1438.7 (1985K$)

| | TS | DR | MA | TE | RG |
|---|---|---|---|---|---|
| Effort totals | 16.3 | 3.1 | 16.5 | 121.5 | 4.2 |

To build and operate for 10 years at 4380 hours each is $1776 K.

Costs to Engineer-Design-Inspect-Administrate are 0% of the costs to build.

TABLE VII
Some Design Parameters and Fabrication Costs

| Magnet Type | Number Req.'d | Current (A) | Voltage (V) | ΔT (°C) | Total Mass (Tonne) | Total Power (kW) | Total Water Flow (gpm) | Total Fabrication Costs (K$(85)) |
|---|---|---|---|---|---|---|---|---|
| M | 64 | 792 | 16.5 | 19.5 | 323 | 837 | 164 | 2027.5 |
| QD1 | 32 | 467 | 1.5 | 0.8 | 6 | 22 | 101 | 430.0 |
| QF2 | 32 | 493 | 8.5 | 12.6 | 43 | 134 | 41 | 660.0 |
| QD3 | 32 | 493 | 6.1 | 7.7 | 31 | 97 | 48 | 593.1 |
| QD4 | 64 | 467 | 2.9 | 2.3 | 29 | 86 | 141 | 908.1 |
| QF5/QD6 | 96 | 467 | 3.7 | 3.5 | 52 | 167 | 184 | 1438.7 |
| QF7 | 32 | 467 | 4.0 | 3.8 | 21 | 59 | 59 | 521.1 |
| Totals for Ring | | | | | 505 | 1402 | 738 | 6578.5 |

## TRIM CALCULATIONS

To address the field errors of the dipole magnets, we have done several magnetic field calculations. A TRIM calculation was done for a flat pole version of the magnet. This utilized a relatively high resolution mesh that could be altered at a later date to incorporate some edge shims. The mesh generated is shown in Figure 3 and a plot of the field lines is shown in Figure 4. The calculated midplane vertical field strengths across the gap are shown in Figure 5 (followed by tabulated values). The right hand edge of this plot also represents the shape of the end field. Figure 6 shows an expanded view around the gap center. Also a plot was made for the radial field component, at y = 1.5 cm, near the gap center as shown in Figure 7 (followed by tabulated values). This TRIM run also provided the forces on the coils. The TRIM data tape could also be used to calculate the forces between the poles so a more accurate calculation of the pole deflections could be carried out in the future.

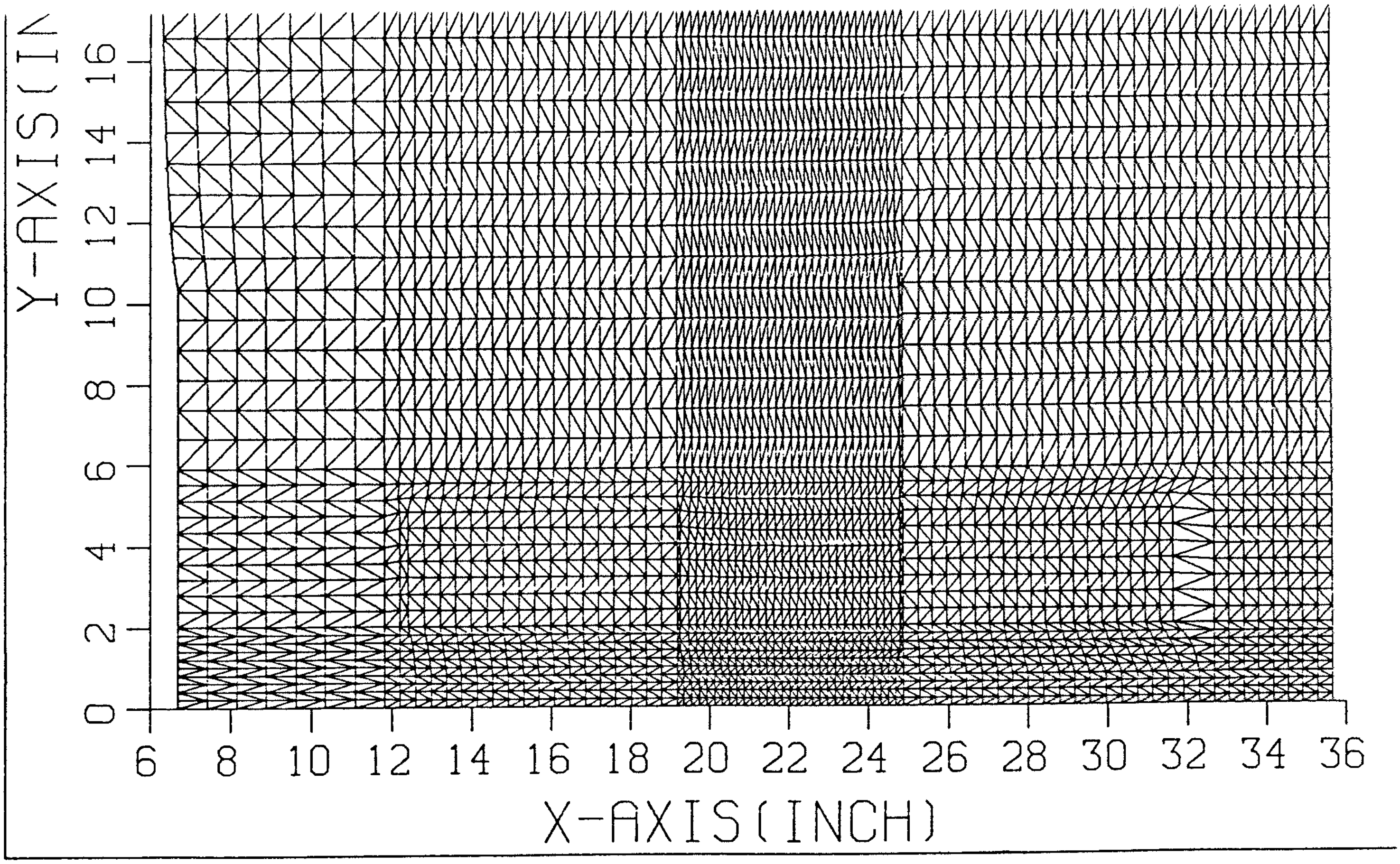



Figure 3 - Mesh for the Storage Ring Dipole

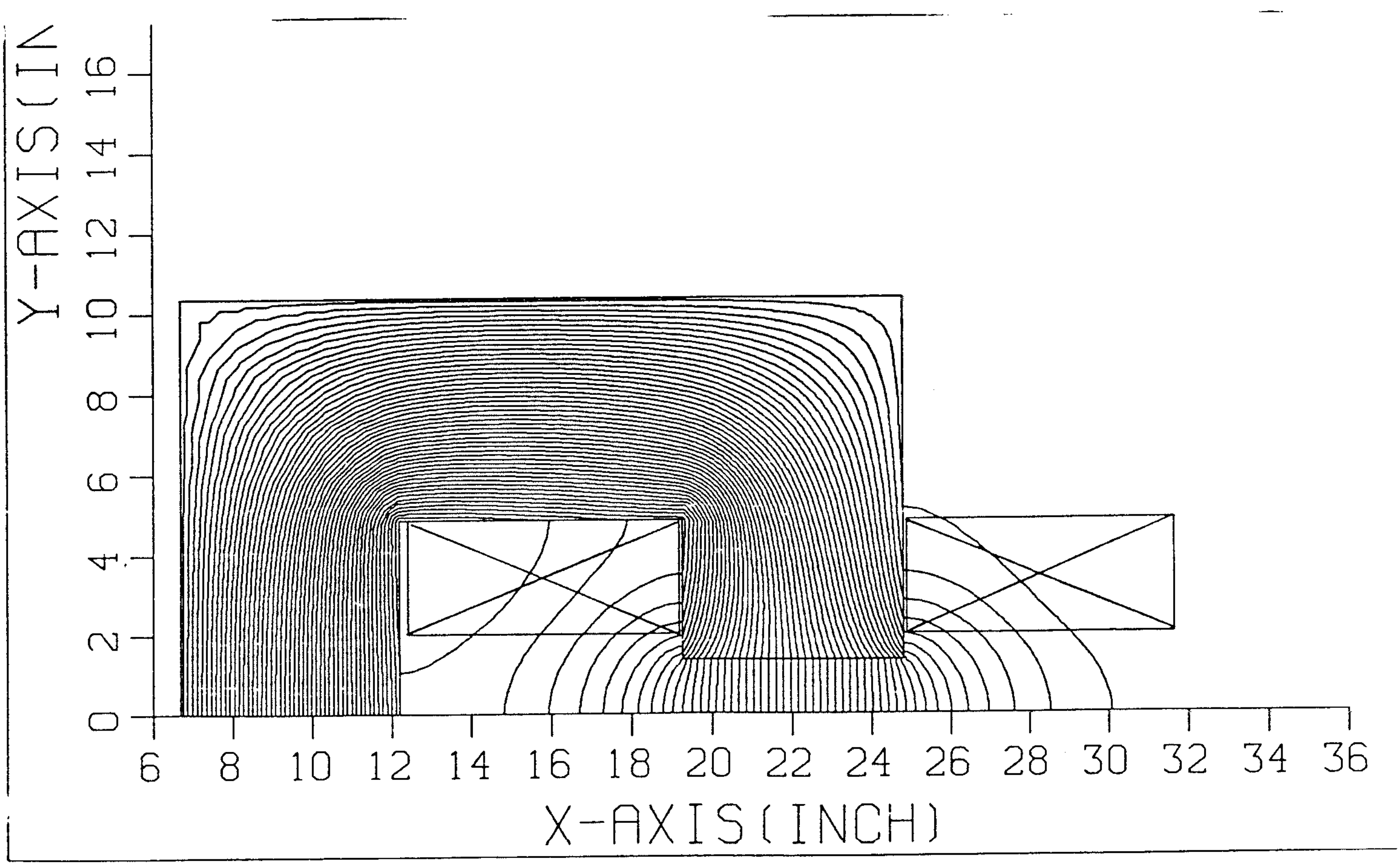



Figure 4 - Field Lines in the Storage Ring Dipole

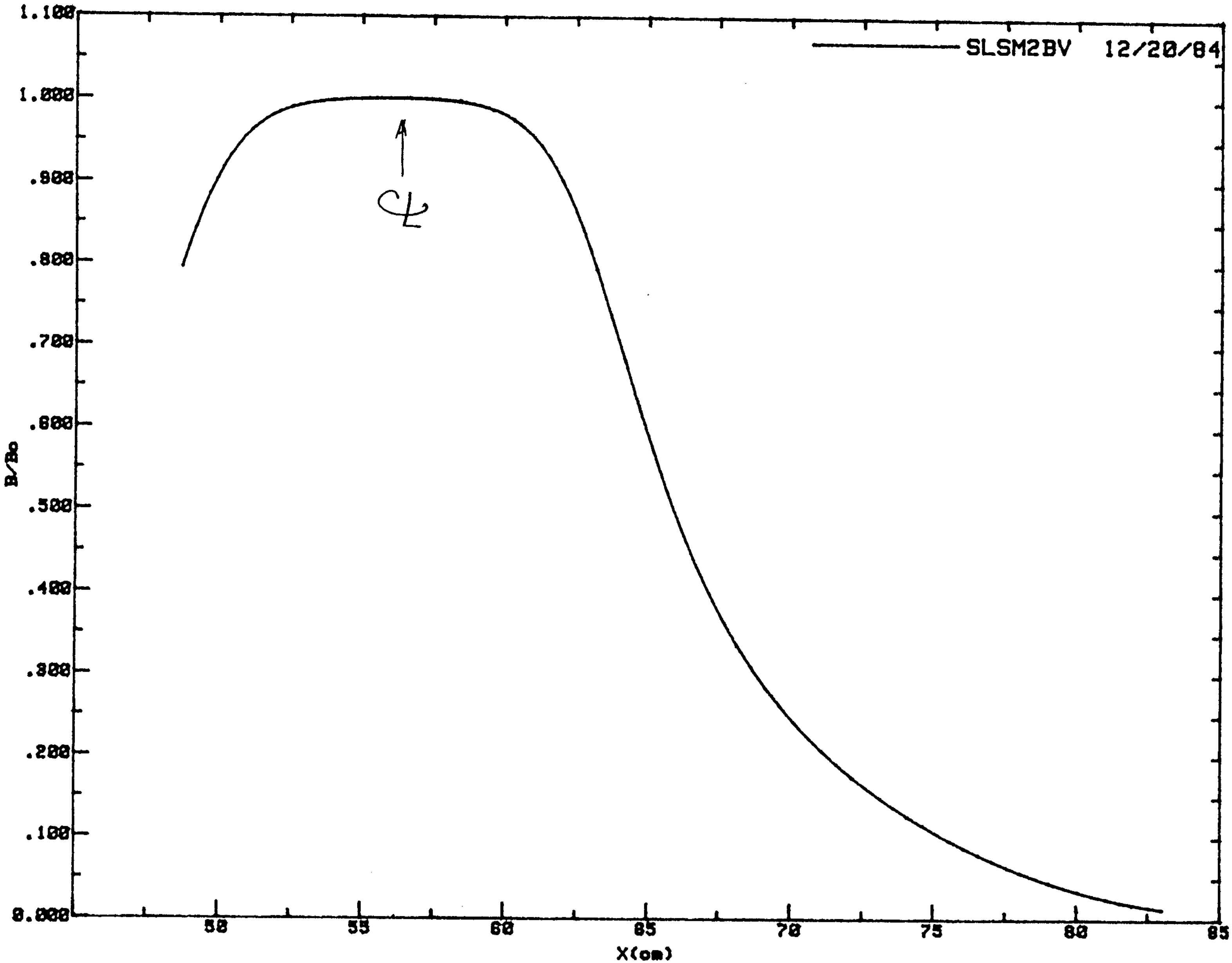



Figure 5 - Vertical Field along a radial line in the midplane of the Storage Ring Dipole

Vertical field strengths on the midplane
as calculated with TRIM

SLSM2B 6.5cm x 14cm Gap + 14cm Yoke VERTICAL

The value of Bo used in the following list is 6661.99.

The input coordinate pairs are (X,B) and pairs to be plotted are (X,B/Bo):

| # | X | B(Gauss) | X(cm) | B/Bo |
|---|---|---|---|---|
| 1 | 48.7000 | 5292.6600 | 48.7000 | 0.79446 |
| 2 | 49.1833 | 5615.9600 | 49.1833 | 0.84299 |
| 3 | 49.6666 | 5891.9600 | 49.6666 | 0.88441 |
| 4 | 50.1499 | 6113.1600 | 50.1499 | 0.91762 |
| 5 | 50.6332 | 6281.2900 | 50.6332 | 0.94285 |
| 6 | 51.1165 | 6403.8600 | 51.1165 | 0.96125 |
| 7 | 51.5998 | 6490.4200 | 51.5998 | 0.97425 |
| 8 | 52.0831 | 6550.1500 | 52.0831 | 0.98321 |
| 9 | 52.5667 | 6590.6700 | 52.5667 | 0.98929 |
| 10 | 53.0500 | 6617.8000 | 53.0500 | 0.99337 |
| 11 | 53.5333 | 6635.7600 | 53.5333 | 0.99606 |
| 12 | 54.0167 | 6647.4900 | 54.0167 | 0.99782 |
| 13 | 54.5000 | 6654.9900 | 54.5000 | 0.99895 |
| 14 | 54.9833 | 6659.5500 | 54.9833 | 0.99963 |
| 15 | 55.4667 | 6661.9900 | 55.4667 | 1.00000 |
| 16 | 55.9500 | 6662.7400 | 55.9500 | 1.00011 |
| 17 | 56.4333 | 6661.9400 | 56.4333 | 0.99999 |
| 18 | 56.9167 | 6659.4600 | 56.9167 | 0.99962 |
| 19 | 57.4000 | 6654.8400 | 57.4000 | 0.99893 |
| 20 | 57.8833 | 6647.2900 | 57.8833 | 0.99779 |
| 21 | 58.3667 | 6635.4800 | 58.3667 | 0.99602 |
| 22 | 58.8500 | 6617.4100 | 58.8500 | 0.99331 |
| 23 | 59.3333 | 6590.1500 | 59.3333 | 0.98922 |
| 24 | 59.8167 | 6549.4500 | 59.8167 | 0.98311 |
| 25 | 60.3000 | 6489.4600 | 60.3000 | 0.97410 |
| 26 | 60.7833 | 6402.5100 | 60.7833 | 0.96105 |
| 27 | 61.2667 | 6279.2900 | 61.2667 | 0.94255 |
| 28 | 61.7500 | 6110.0500 | 61.7500 | 0.91715 |
| 29 | 62.2333 | 5887.0200 | 62.2333 | 0.88367 |
| 30 | 62.7167 | 5608.2700 | 62.7167 | 0.84183 |
| 31 | 63.2000 | 5281.1800 | 63.2000 | 0.79273 |
| 32 | 64.1900 | 4543.0700 | 64.1900 | 0.68194 |
| 33 | 65.1800 | 3817.0000 | 65.1800 | 0.57295 |
| 34 | 66.1700 | 3185.0000 | 66.1700 | 0.47809 |
| 35 | 67.1600 | 2664.0000 | 67.1600 | 0.39988 |
| 36 | 68.1500 | 2241.0000 | 68.1500 | 0.33639 |
| 37 | 69.1400 | 1897.0000 | 69.1400 | 0.28475 |
| 38 | 70.1300 | 1613.0000 | 70.1300 | 0.24212 |
| 39 | 71.1200 | 1374.0000 | 71.1200 | 0.20624 |
| 40 | 72.1100 | 1170.0000 | 72.1100 | 0.17562 |
| 41 | 73.1000 | 994.0000 | 73.1000 | 0.14920 |
| 42 | 74.0900 | 839.0000 | 74.0900 | 0.12594 |
| 43 | 75.0800 | 702.0000 | 75.0800 | 0.10537 |
| 44 | 76.0700 | 581.0000 | 76.0700 | 0.08721 |
| 45 | 77.0600 | 473.0000 | 77.0600 | 0.07100 |
| 46 | 78.0500 | 378.0000 | 78.0500 | 0.05674 |
| 47 | 79.0400 | 296.0000 | 79.0400 | 0.04443 |
| 48 | 80.0300 | 226.0000 | 80.0300 | 0.03392 |
| 49 | 81.0200 | 168.0000 | 81.0200 | 0.02522 |
| 50 | 82.0100 | 122.0000 | 82.0100 | 0.01831 |
| 51 | 83.0000 | 87.0000 | 83.0000 | 0.01306 |

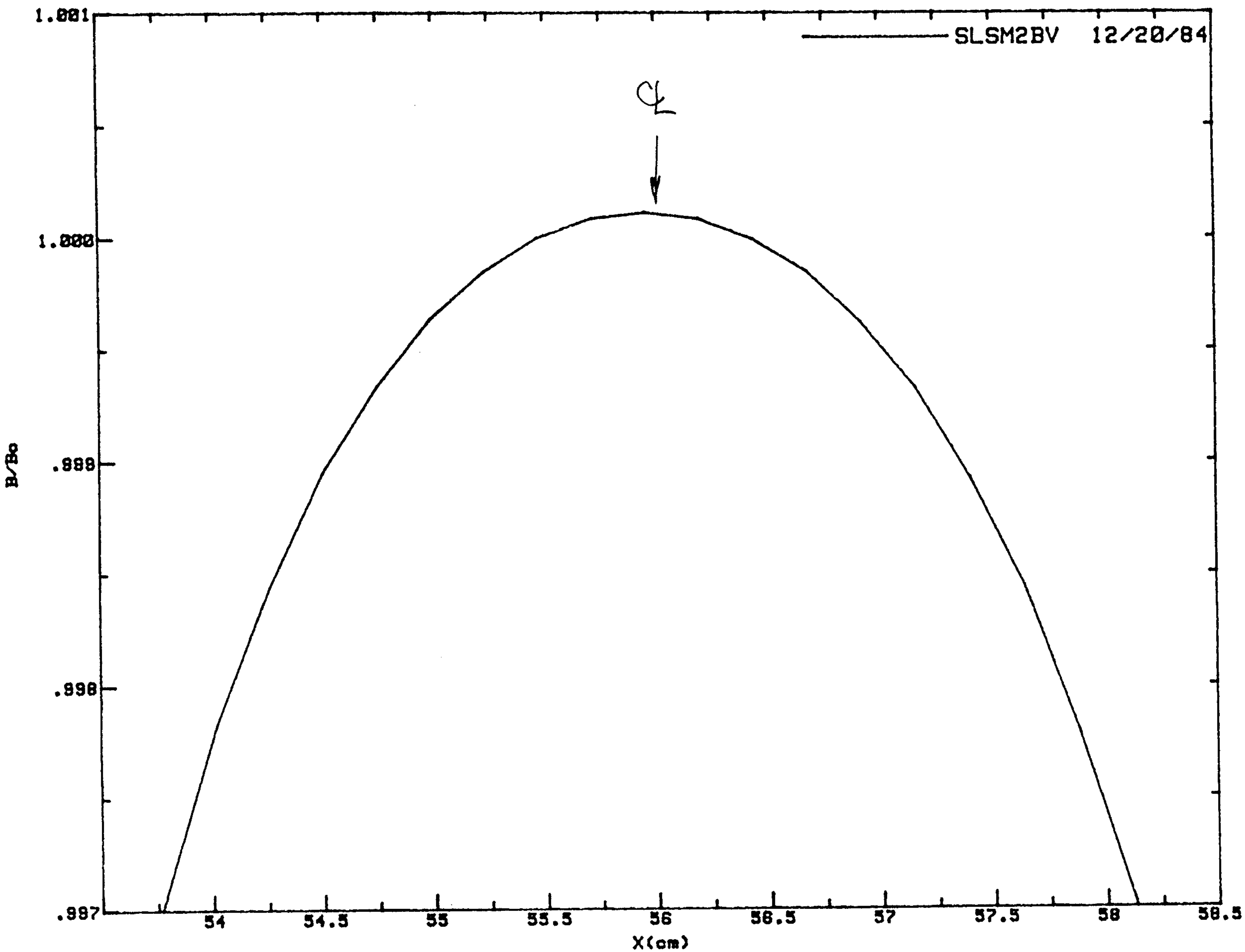



Figure 6 - Vertical Field (expanded) along a radial line on the midplane and near the center of a Storage Ring Dipole

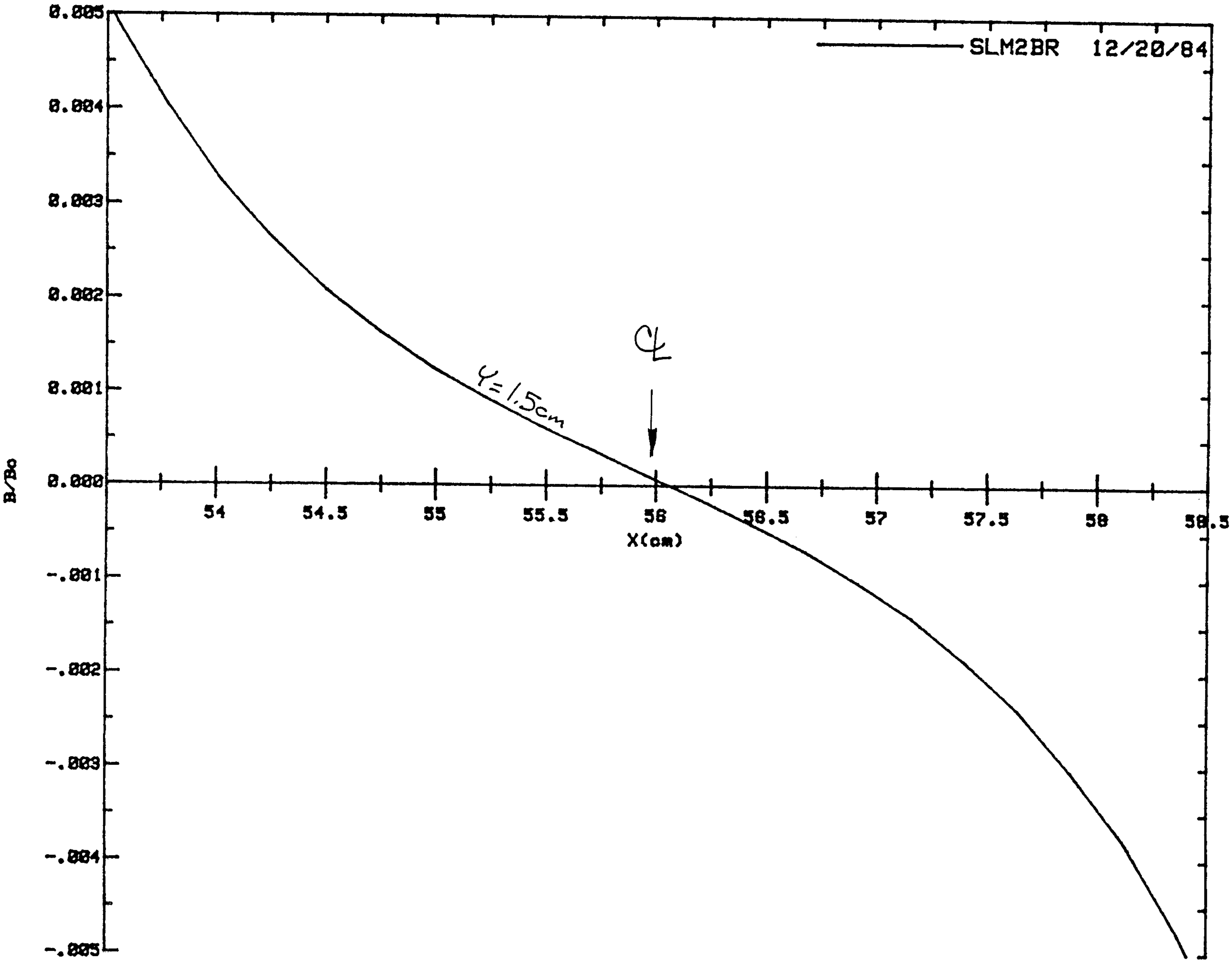



Figure 7 - Radial Field along a radial line, at 1.5 cm above the midplane, in a Storage Ring Dipole

Radial field strengths at y = 1.5 cm above
the midplane as calculated by TRIM

SLM2BR 6.5cm x 14cm Gap + 14cm Yoke RADIAL Z=.5

The value of Bo used in the following list is 6661.99.

The input coordinate pairs are (X,B) and pairs to be plotted are (X,B/Bo):

| # | X | B(Gauss) | X(cm) | B/Bo |
|---|---|---|---|---|
| 1 | 53.0500 | 22.4700 | 53.0500 | 0.00337 |
| 2 | 53.5333 | 15.0500 | 53.5333 | 0.00226 |
| 3 | 54.0167 | 10.0500 | 54.0167 | 0.00151 |
| 4 | 54.5000 | 6.6200 | 54.5000 | 0.00099 |
| 5 | 54.9833 | 4.2100 | 54.9833 | 0.00063 |
| 6 | 55.4667 | 2.3800 | 55.4667 | 0.00036 |
| 7 | 55.9500 | 0.8300 | 55.9500 | 0.00012 |
| 8 | 56.4333 | -.7300 | 56.4333 | -.00011 |
| 9 | 56.9167 | -2.5600 | 56.9167 | -.00038 |
| 10 | 57.4000 | -4.9800 | 57.4000 | -.00075 |
| 11 | 57.8833 | -8.4200 | 57.8833 | -.00126 |
| 12 | 58.3667 | -13.4300 | 58.3667 | -.00202 |

## PE2D CALCULATIONS

In addition to the TRIM magnetic field calculations, the computer program PE2D was used to check these results and we tried to utilize the TRACKING feature to track electron through the end field. Preliminary tracking results are shown below. The field values are given in TABLE VIII and plotted in Figure 8 for both the area under the pole and the end field region. They agree with TRIM to a reasonable accuracy.

```
TRACK STARTING PARAMETER
FIELD FACTOR=    1 00 TOL=    0 0100000  STEP=     0 1000
MAX NO OF STEPS=  200 ZMAX=    40 000 ZMIN=     0 000 IFLDT=    1
TRACK     Z0          X0          V          THETA       PHI        MASS        AMPS
  1       0 010      38.950 6 000E+09      90 000       0 000       0 000 1 00000
NIT=     0 NITD=     0
General ray tracing option
Fields from PE2D
Magnetic field
Electrons
 BFAC=       1.000
 TOLERANCE=        0 0100
 STARTING PARAMETERS  VOLTS= 6 000E+09 ANGLE=   90 000 PHI=      0 000
 X0=     38 950 Z0=       0.010 VELOCITY= 2 998E+08 M/SEC
 TRACK NUMBER       1
 ISTEP       T          Z           X          PHI        ANGLE       BZ          BX
     0   0 000000   0 010000   38 9500   0 000000   90 0000    6660 98   -0 15180
3   10   3 34E-11   0 010000   39.9500   0 014476   90 0000    6658 37   -1 57566
    20   6 67E-11   0.010000   40 9494   0 056469   90 0000    6648 29   -4 35194
    30   1 00E-10   0 009999   41 9481   0 123931   90 0000    6621 50   -11 2060
    40   1 33E-10   0 009996   42 9457   0.214938   90.0003    6554.81   -27 0664
    50   1 67E-10   0 009986   43.9416   0.327483   90 0010    6397.32   -60 6018
    60   2 00E-10   0.009956   44 9357   0.459400   90.0027    6060 72   -117 046
    70   2 33E-10   0.009884   45.9274   0.608094   90.0060    5421.97   -175 030
    80   2 67E-10   0.009742   46.9171   0.770284   90.0107    4687 98   -192 003
    90   3 00E-10   0.009514   47.9047   0.942490   90 0158    3905.50   -174 520
   100   3.34E-10   0.009200   48.8903   1.12142    90 0204    3219.09   -144 197
   110   3 67E-10   0 008811   49.8742   1 30436    90 0246    2667.20   -114 806
   120   4 00E-10   0 008358   50.8567   1.48920    90 0280    2230 40   -91 7007
   130   4 34E-10   0 007853   51.8379   1 67438    90 0308    1877 13   -73 9364
   140   4 67E-10   0 007303   52.8179   1 85873    90 0331    1589 50   -60 5202
   150   5 00E-10   0 006716   53 7970   2 04142    90 0350    1355 60   -50 8616
   160   5 34E-10   0 006098   54 7751   2 22178    90 0369    1156 42   -43 3758
   170   5 67E-10   0 005452   55 7527   2 39930    90 0383    984 383   -37 5014
   180   6 00E-10   0 004781   56 7296   2.57366    90 0397    836 288   -32 8340
   190   6 34E-10   0.004029   57 7059   2 74452    90 0409    705 954   -29 0113
   200   6 67E-10   0 003378   58 6818   2 91173    90 0419    589 876   -25 6930
End of track
OK
```

TABLE VIII-A

| (cm) X position | $B_y(y = 0)$ Value | $B_y$ (y = 1.5) Value | $B_x$ Value | (GAUSS) $B_y$ (y = 3.0) Value | $B_x$ Value |
|---|---|---|---|---|---|
| 31 9500 | 5226 28 | 5450 23 | 1249 24 | 6655.49 | 4360 3.. |
| 32 4500 | 5750 86 | 6132 04 | 965 178 | 8403 10 | 1776 80 |
| 32 9500 | 6028 86 | 6384.69 | 675 299 | 7638 22 | 670 038 |
| 33 4500 | 6236 28 | 6519.22 | 448 907 | 7224 77 | 303 910 |
| 33 9500 | 6383 19 | 6588 27 | 290 392 | 6995 01 | 156 443 |
| 34, 4500 | 6483 14 | 6624 51 | 185.087 | 6863.24 | 86.8878 |
| 34 9500 | 6549 10 | 6643 08 | 116.520 | 6786 12 | 50.1020 |
| 35 4500 | 6592 02 | 6652 81 | 73.1099 | 6740 00 | 30.1290 |
| 35 9500 | 6619 60 | 6658 43 | 45.5580 | 6711 98 | 18.3911 |
| 36 4500 | 6636 91 | 6661 70 | 28 3500 | 6694 89 | 11.1673 |
| 36 9500 | 6647 64 | 6663.58 | 17.4251 | 6684 28 | 6.73057 |
| 37 4500 | 6654 37 | 6664.67 | 10.3883 | 6677.97 | 4.00117 |
| 37 9500 | 6658.22 | 6665.28 | 5.81848 | 6674 32 | 2.20156 |
| 38 4500 | 6660.20 | 6665.51 | 2.53010 | 6672.27 | 0.899289 |
| 38 9500 | 6660.97 | 6665 64 | -0.101800 | 6671.50 | -0.209888 |
| 39 4500 | 6660.37 | 6665.62 | -2.67961 | 6672.07 | -1.16854 |
| 39 9500 | 6658.34 | 6665.36 | -5.84786 | 6673.96 | -2.22562 |
| 40 4500 | 6654.50 | 6664 92 | -10.2854 | 6677.40 | -3.71544 |
| 40.9500 | 6648.23 | 6664.21 | -17.0491 | 6683.54 | -6.07600 |
| 41 4500 | 6637.84 | 6662.87 | -27.6441 | 6693.64 | -9.83560 |
| 41 9500 | 6621.34 | 6660 50 | -44 4728 | 6710.49 | -15.6620 |
| 42 4500 | 6595.16 | 6656.43 | -71.2847 | 6738.24 | -25.4003 |
| 42 9500 | 6554.24 | 6648.66 | -114.016 | 6784.02 | -42.0960 |
| 43 4500 | 6491.02 | 6633.61 | -181.399 | 6861.40 | -71.5110 |
| 43 9500 | 6395 28 | 6603 24 | -286.378 | 6996.04 | -127 089 |
| 44 4500 | 6254 13 | 6540.32 | -445 497 | 7242.19 | -244.113 |
| 44.9500 | 6054 34 | 6410 60 | -673 000 | 7731.07 | -534.940 |
| 45.4500 | 5786 20 | 6154.40 | -960.080 | 8842.86 | -1429.21 |

FIGURE 8A

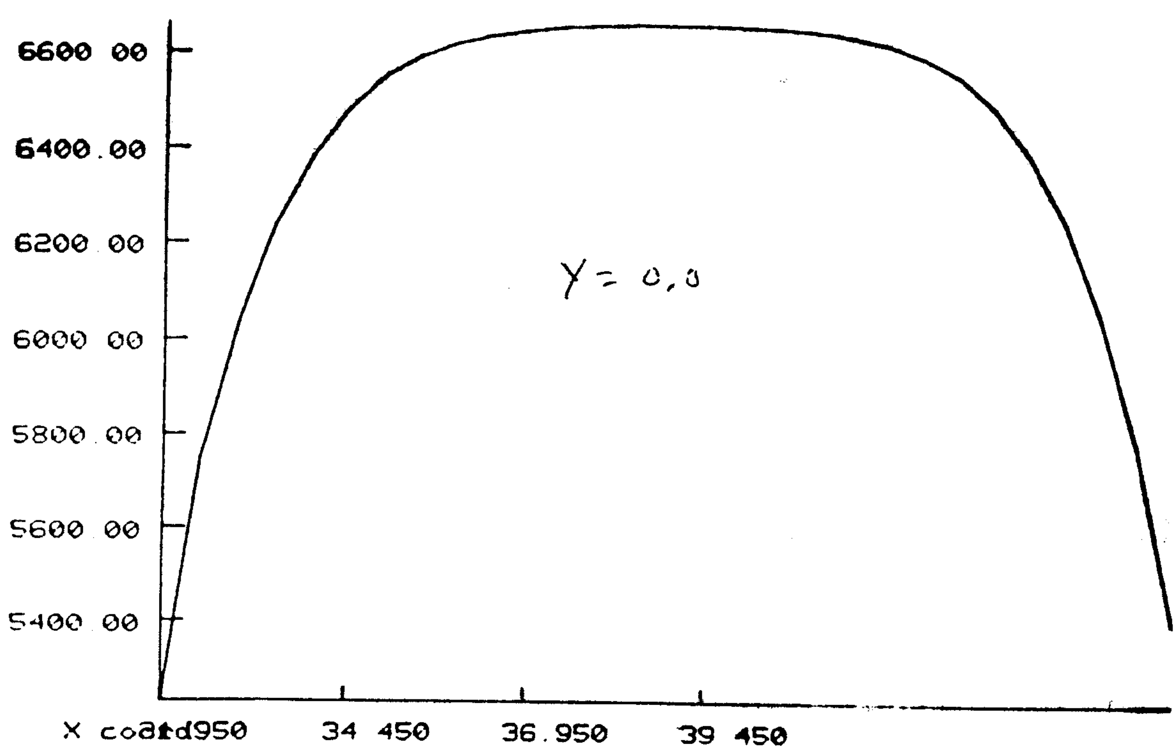
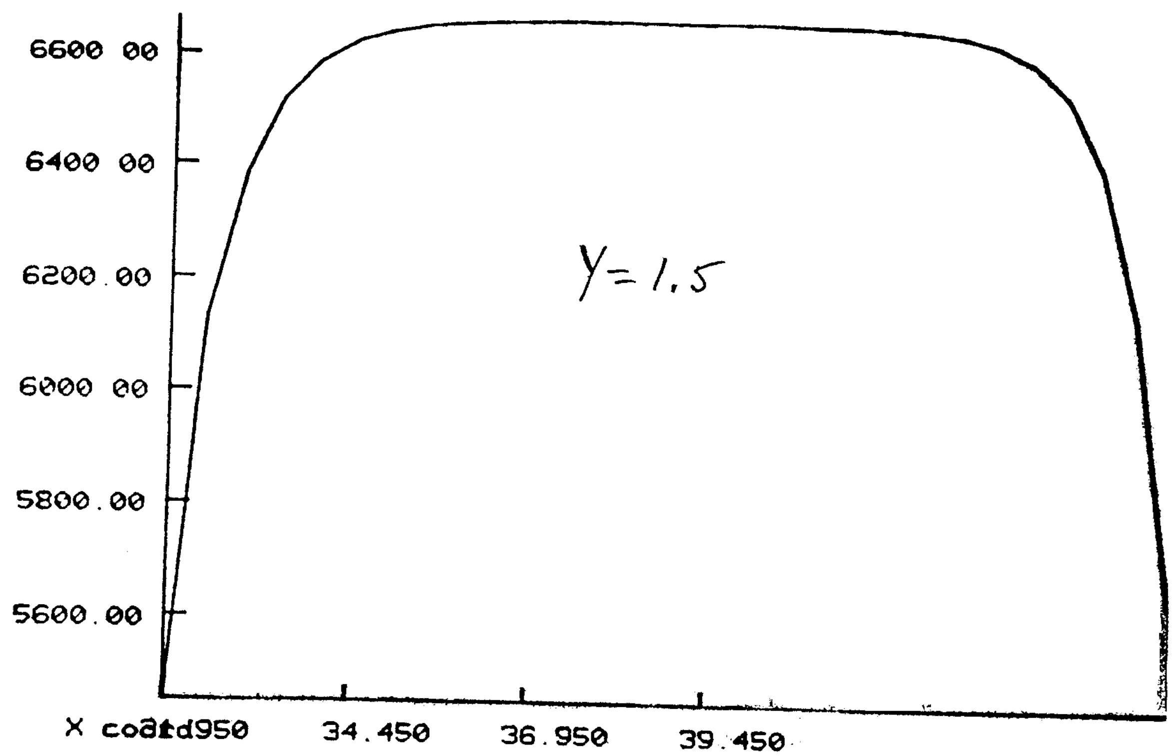
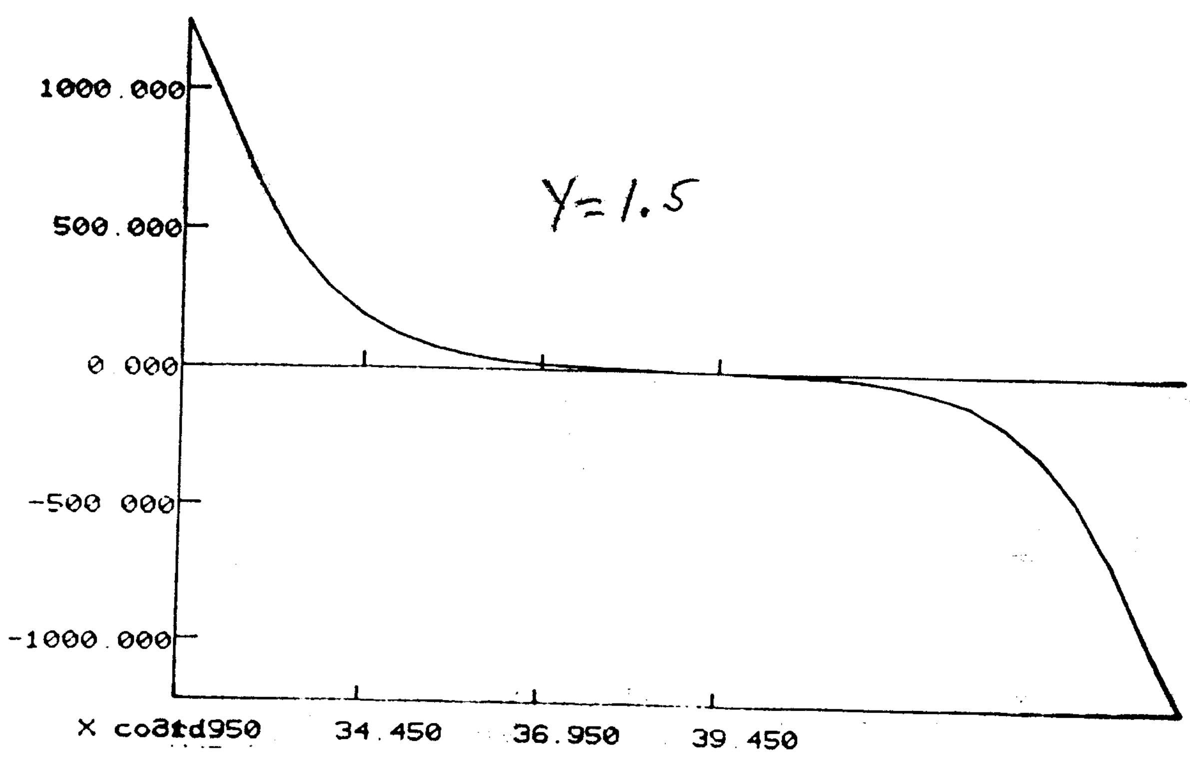


FIGURE 8B

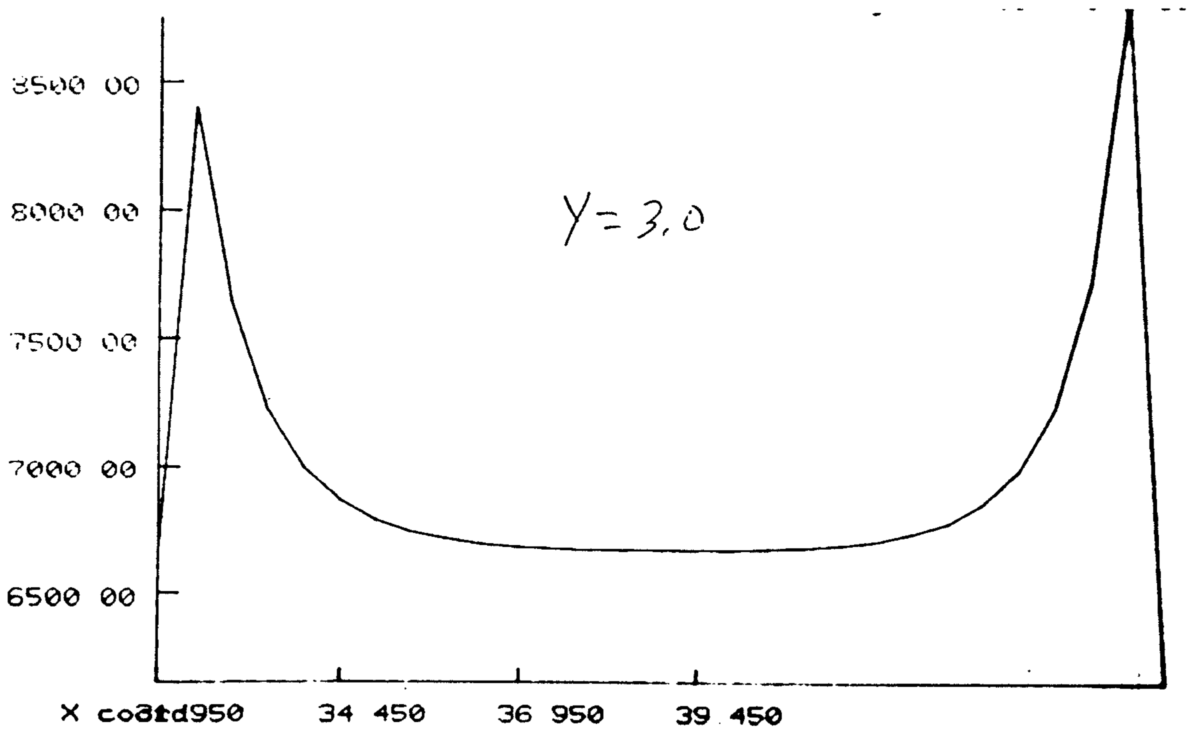


6600 00
6400 00
6200.00
6000 00
5800.00
5600.00
Y=1.5
X coord950
34.450
36.950
39.450

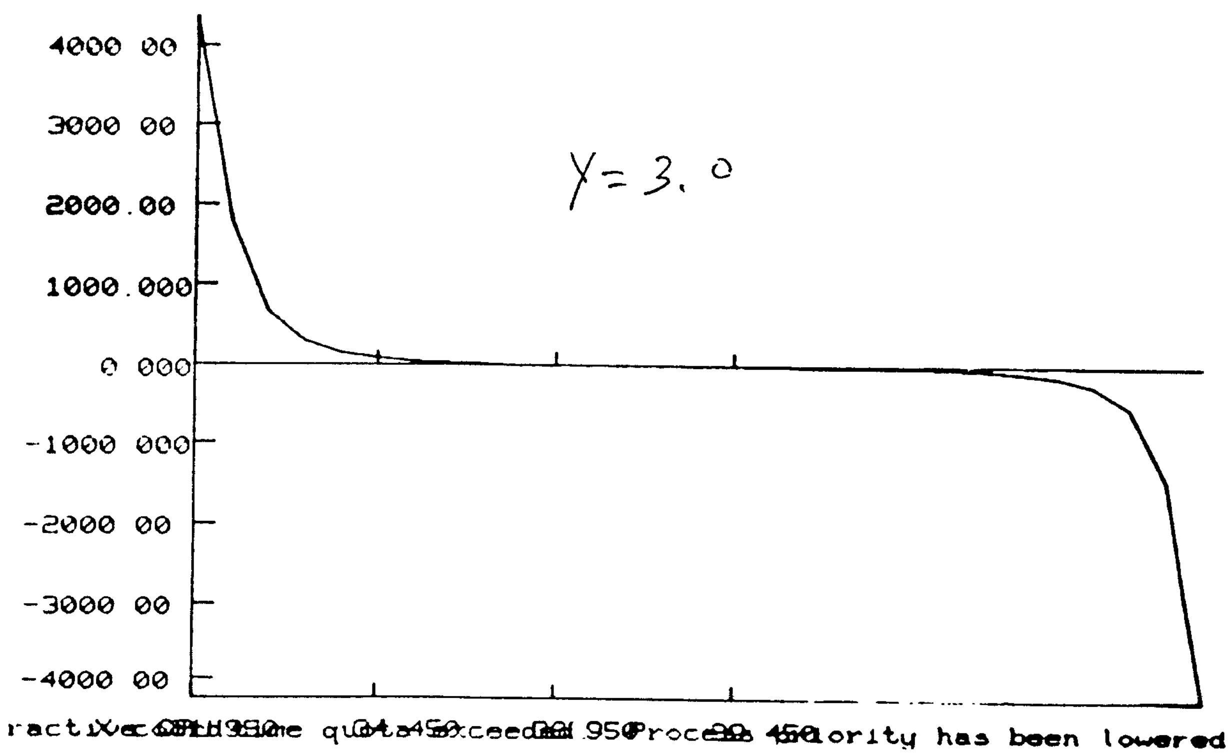



1000.000
500.000
0 000
-500 000
-1000.000
Y=1.5
X coord950
34.450
36.950
39.450

FIGURE 8C



8500 00
8000 00
7500 00
7000 00
6500 00
Y=3.0
X coord
34 450
36 950
39 450

4000 00
3000 00
2000.00
1000.000
0 000
-1000 000
-2000 00
-3000 00
-4000 00
Y=3.0
ority has been lowered

| position (cm) | $B_y$ (y = 0) Value | $B_y$ (y = 1.5) Value | $B_x$ Value (GAUSS) | $B_y$ (y = 3.0) Value | $B_x$ Value |
|---|---|---|---|---|---|
| 38 9500 | 6660 97 | 6665 64 | -0 101800 | 6671 50 | -0 209339 |
| 39 9500 | 6658 34 | 6665 36 | -5 84786 | 6673 96 | -2 22562 |
| 40 9500 | 6648 23 | 6664 21 | -17 0491 | 6683 54 | -6 07600 |
| 41 9500 | 6621 34 | 6660 50 | -44 4728 | 6710 49 | -15 6620 |
| 42 9500 | 6554 24 | 6643 66 | -114 016 | 6784 02 | -42 0960 |
| 43 9500 | 6395 28 | 6603 24 | -286 378 | 6996 04 | -127 089 |
| 44 9500 | 6054 34 | 6410 60 | -673 000 | 7731 07 | -534 940 |
| 45 9500 | 5404 37 | 5634 60 | -1224 30 | 6160 01 | -4251 30 |
| 46 9500 | 4661 32 | 4621 50 | -1307 77 | 4075 37 | -3247 14 |
| 47 9500 | 3871 30 | 3722 88 | -1139 93 | 3062 27 | -2320 92 |
| 48 9500 | 3179 68 | 3020 20 | -914 803 | 2490 04 | -1720 20 |
| 49 9500 | 2631 63 | 2504 34 | -713 227 | 2120 94 | -1323 88 |
| 50 9500 | 2193 60 | 2096 39 | -566 918 | 1822 13 | -1048 46 |
| 51 9500 | 1839 69 | 1767 29 | -456 852 | 1566 72 | -851 066 |
| 52 9500 | 1556 90 | 1504 21 | -374 010 | 1355 30 | -707 309 |
| 53 9500 | 1322 60 | 1282 56 | -314 889 | 1171 20 | -599 278 |
| 54 9500 | 1123 11 | 1092 19 | -269 242 | 1005 92 | -516 850 |
| 55 9500 | 953 201 | 929 021 | -232 886 | 860 634 | -451 949 |
| 56 9500 | 805 809 | 786 067 | -204 694 | 730 511 | -399 383 |
| 57 9500 | 675 266 | 652 452 | -181 296 | 611 044 | -356 161 |
| 58 9500 | 560 193 | 545 239 | -160 469 | 502 796 | -318 103 |
| 59 9500 | 459 137 | 445 060 | -141 620 | 404 788 | -282 418 |
| 60 9500 | 369 816 | 356 016 | -123 811 | 315 736 | -248 241 |
| 61 9500 | 292 523 | 278 791 | -105 684 | 237 394 | -212 408 |
| 62 9500 | 223 828 | 210 529 | -87 3798 | 169 564 | -173 324 |
| 63 9500 | 170 010 | 158 120 | -69 9417 | 121 436 | -136 544 |
| 64 9500 | 131 260 | 120 828 | -55 0478 | 88 9042 | -104 349 |
| 65 9500 | 99 8953 | 91 5049 | -42 5021 | 66 3911 | -79 4392 |
| [illegible] | 73 8070 | 67 2870 | -32 0678 | 47 6297 | -59 7414 |
| 67 9500 | 52 9940 | 47 8360 | -24 2670 | 32 8699 | -44 4417 |
| 68 9500 | 39 2080 | 35 3107 | -18 4840 | 24 0470 | -33 8477 |
| 69 9500 | 27 7387 | 24 8557 | -13 7824 | 16 3170 | -25 4343 |
| 70 9500 | 18 2808 | 16 6532 | -10 4374 | 10 2856 | -19 0543 |
| 71 9500 | 12 3770 | 11 2090 | -7 94970 | 6 42776 | -14 5563 |
| 72 9500 | 7 90496 | 6 67679 | -5 93617 | 3 03662 | -10 9934 |
| 73 9500 | 4 13366 | 3 17901 | -4 53010 | 0 450518 | -8 29949 |
| 74 9500 | 1 50183 | 0 783658 | -3 45046 | -1 27722 | -6 33289 |

FIGURE 8D

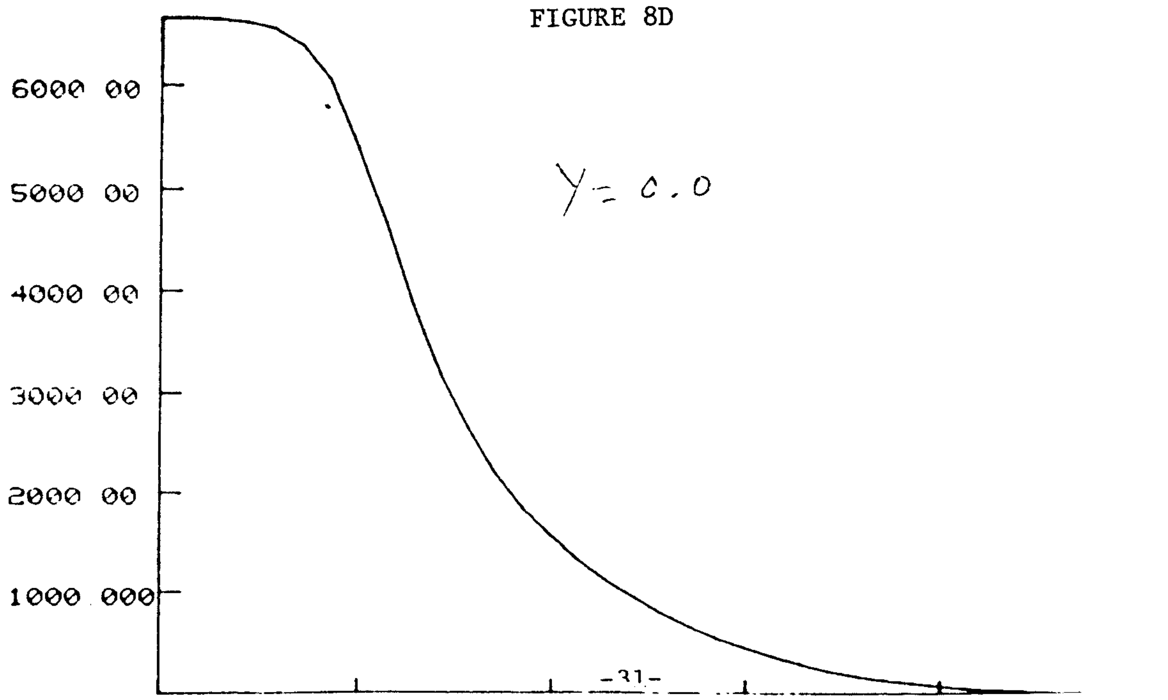


FIGURE 8E

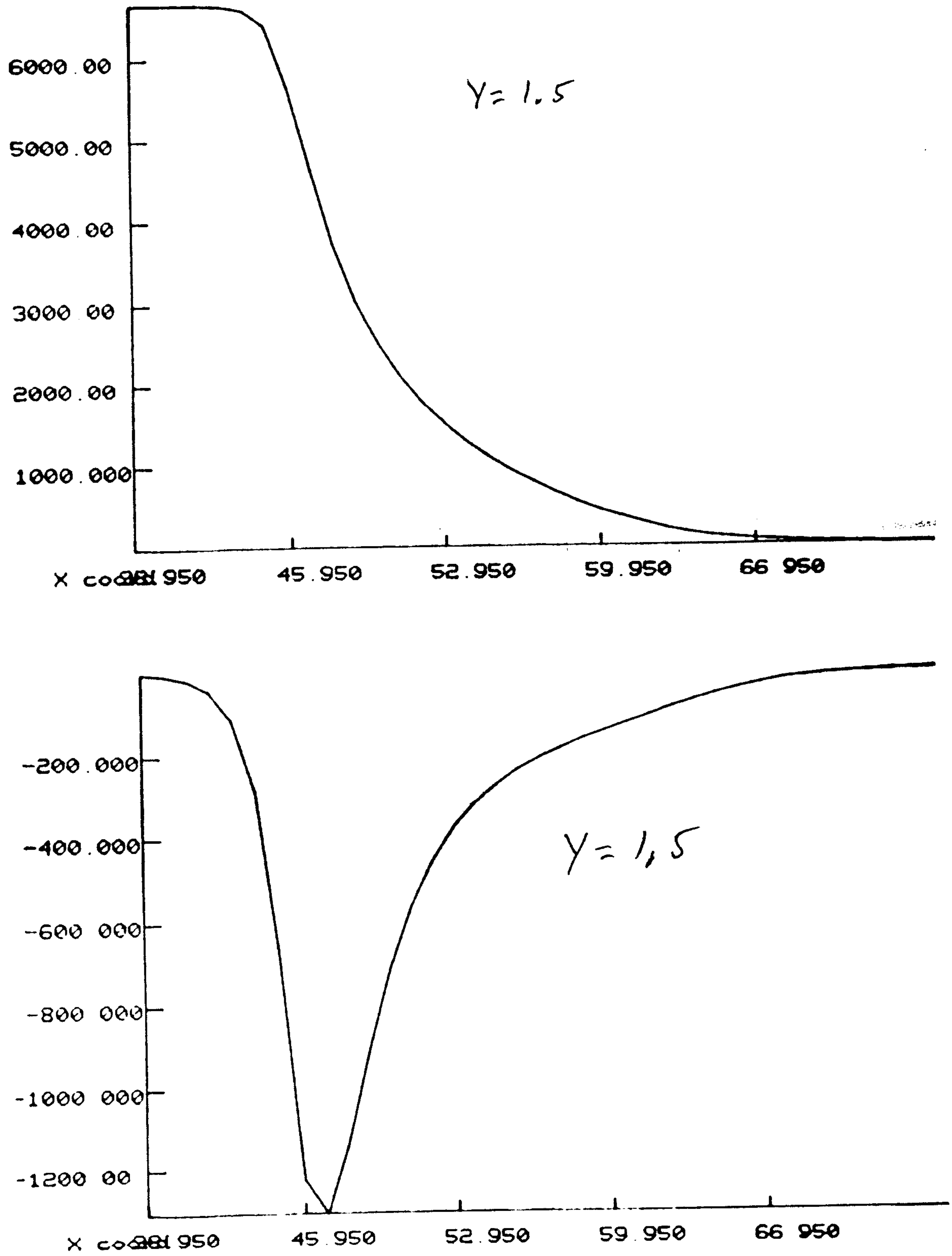
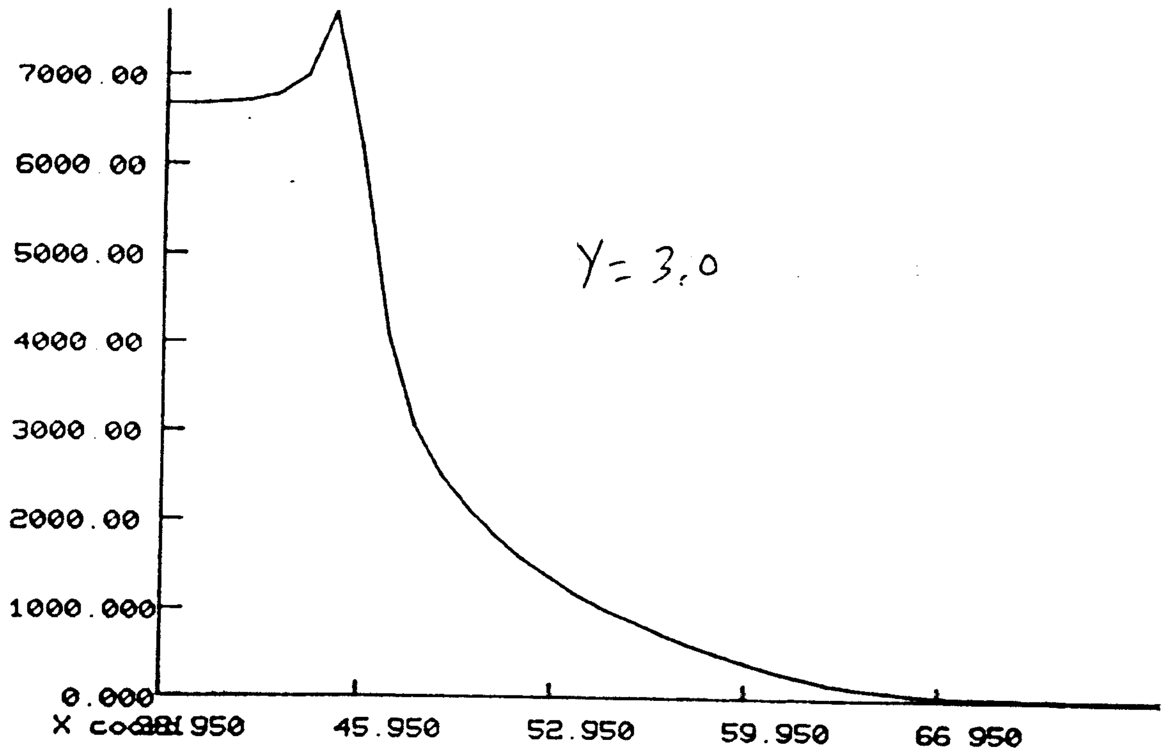
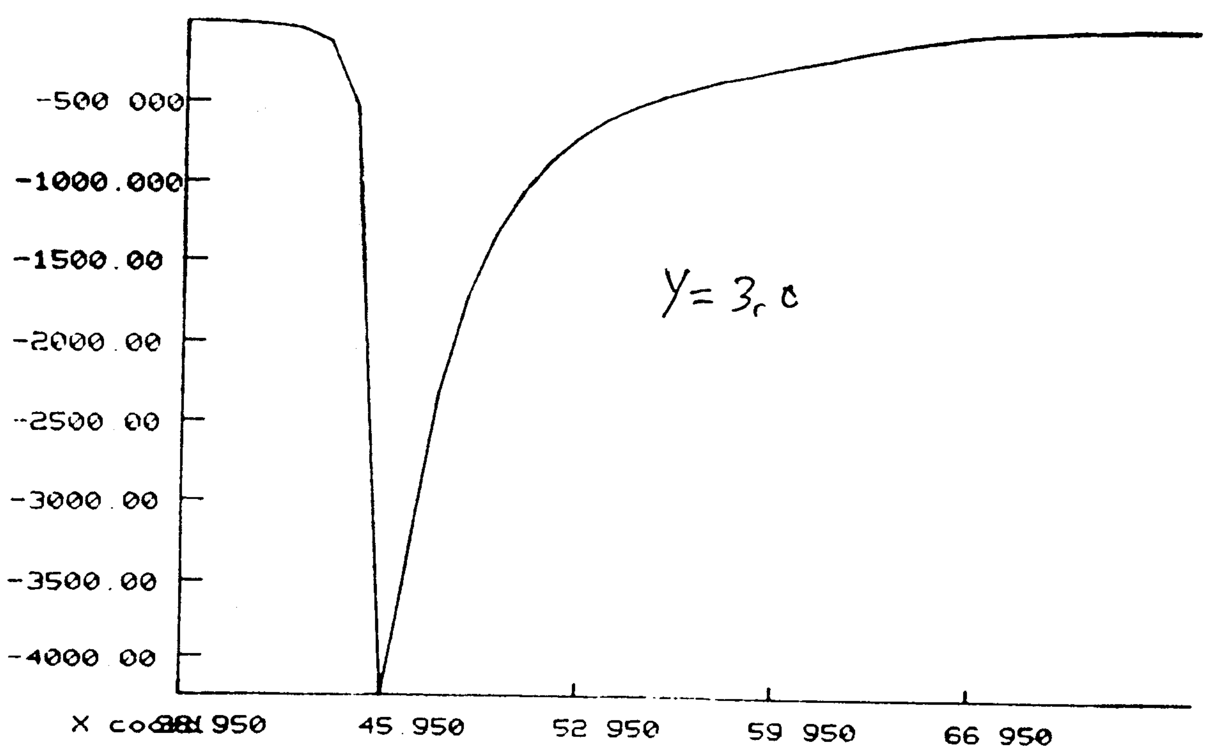

6000.00
5000.00
4000.00
3000.00
2000.00
1000.000
Y= 1.5
X coord 38.950
45.950
52.950
59.950
66.950
-200.000
-400.000
-600.000
-800.000
-1000.000
-1200.00
Y= 1,5
X coord 38.950
45.950
52.950
59.950
66.950

FIGURE 8F


7000.00
6000.00
5000.00
4000.00
3000.00
2000.00
1000.000
0.000
X co38.950
45.950
52.950
59.950
66 950
Y= 3.0


-500 000
-1000.000
-1500.00
-2000.00
-2500 00
-3000.00
-3500.00
-4000 00
X co38.950
45 950
52 950
59 950
66 950
Y= 3.0

## POISSON CALCULATIONS

POISSON is a next generation of TRIM and the mesh is set up in a similar manor. It has one feature in it that TRIM does not have, namely, the field can be analyzed in terms of the harmonic content. For a dipole field with symmetry, only the odd harmonies can be present, namely m=1 (dipole), 3 (sextupole), 5,7, etc. A calculation that was not fully converged (due to other problems) had the harmonic fields as shown in TABLE IX.

TABLE IX

Harmonic content in the storage ring dipole

| N | Bn (at $r_o$=2.54 cm) |
|---|---|
| 1 | 6634.7 |
| 3 | 6.6 |
| 5 | 15.6 |
| 7 | 2.1 |
| 9 | 7.5 |

Remember, that at a smaller radius, the field will fall off as $(r/r_o)^{N-1}$ so the higher harmonies fall off very fast as the radius decreases. For a fully converged solution, these higher harmonics should be smaller.

## FUTURE CALCULATIONS

There still is more that can be done to fine tune the designs for the storage ring magnets. The cores and coils must be optimized to some degree. Shims could be developed for the edges of the poles in the dipoles. This can be done in a fairly short time (1 week) for the dipoles, but doing it for the quadrupoles would be more time consumming since there are four different designs and the geometry is much more complex to set up than for a dipole. A 3 dimensional calculation using TOSCA would be needed to calculate the harmonics due to the edge fields of the magnets.